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6. AUTHOR(S)
Julian D. Maynard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Pennsylvania State University
Department of Physics
104 Davey Lab
University Park, PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER

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The goals of this project involve the use of innovative acoustic techniques to study new materials and new developments in solid state physics, such as effects in mesoscopic electronic systems. Major accomplishments include a) the preparation and publication of a number of major papers and chapters in books, b) the comparison of the anisotropy of an aluminum alloy quasicrystal with that of its cubic approximant, c) the measurement of the elastic constants of a diamond substitute material, TiB_2, d) the measurement of an extremely low (possible the lowest) infrared optical absorption coefficient, e) the measurement of the effects of disorder on the propagation of a nonlinear pulse, and f) the acquisition of initial data in an experiment on the onset of fracture.

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INNOVATIVE TECHNIQUES FOR STUDYING NEW MATERIALS AND NEW DEVELOPMENTS IN SOLID STATE PHYSICS

This report summarizes the goals and accomplishments for ONR grant N00014 -92-J-1186,"Innovative Acoustic Techniques for Studying New Materials and New Developments in Solid State Physics". The goals of the project are a) to use resonant ultrasound spectroscopy to study new materials, such as quasicrystals and diamond substitute materials such as TiB_2, b) to use a resonant photoacoustic technique to measure infrared optical absorption in highly transparent materials, c) the use of acoustic analogs to study effects analogous to those of mesoscopic electronic systems, and d) the study of fracture in brittle materials. The research involved four graduate students (including two employed during the summer), a post-doc, and three undergraduate students.

Published papers, submitted papers, talks, etc.

A complete list of publications, talks, etc. is presented in the appendix. To summarize, there were three papers published in refereed journals, including one in the prestigious Physical Review Letters, and three chapters published in books. In addition, three other papers have been accepted for publication in a refereed journal, and two other book chapters are pending publication. A number of invited talks describing our research were given: there were three lectures at universities, and three invited lectures national meetings, including an invited lecture at the prestigious International Conference on Low Temperature Physics. There were also eight contributed papers at national meetings.

In the sections which follow, a brief summary of the research accomplishments will be presented.

General progress in the development of Resonant Ultrasound Spectroscopy

In the resonant ultrasound research, significant advances were made in trans-

ducer fabrication, data acquisition and analysis, and perhaps most importantly, sample preparation. Samples of only 100 μg mass have been measured. The graduate student has written new computer programs which obtain nonlinear fits to the resonant peaks in the data and provide much more precise values for resonance frequencies and attenuation coefficients.

Comparison of the elastic anisotropy of a quasicrystal and its cubic approximant

Since the discovery of quasicrystalline symmetry in solids, there has been considerable interest in determining the consequences of the new symmetry and verifying that actual materials have the properties unique to true quasicrystals. A crucial measurement is the determination of the elastic tensor and the attenuation of the associated sound modes. Theory predicts that a true quasicrystal would be elastically isotropic and have only two independent elastic constants, but there has a controversy as to whether the actual aluminum alloy materials such as AlCuLi are true quasicrystals, or are cubic crystals with large five-fold-symmetric unit cells. Since a cubic material would have three independent elastic constants (apart from an unlikely special case), a vital clue as to the true nature of an actual material would be the measurement of the anisotropy represented by $\epsilon = | 1 - 2C_{44}/(C_{11} - C_{12}) |$. As reported earlier, we measured the lowest and most precise anisotropy of a quasicrystal, $\epsilon = 0.0020 \pm 0.0004$. During this past year we have polished, oriented, and measured the elastic constants and anisotropy of the cubic approximant (R-phase) related to the quasicrystalline phase of AlCuLi. The anisotropy of the cubic approximant, although quite small, was eight times that of the quasicrystal, which adds considerable significance to our earlier measurement of the quasicrystalline isotropy. We have also reproduced our results of the isotropy with a second sample of the quasicrystal, and are currently pursuing a measurement of a second sample of the cubic R-phase, with improved orientation (which is necessary, since it is not isotropic). A paper detailing our results has been prepared, but is currently being rewritten to include the new results.

Measurement of the elastic properties of the diamond substitute TiB_2

We have obtained samples of titanium di-boride (TiB_2), whose hardness is second only to that of diamond, from David Green of the Department of Material Science. Considerable time was spent polishing and orienting the samples. Most samples were only thin ($\sim$20 μm) platelets, having masses of only $\sim$100 μgm. With the piezoelectric film resonant ultrasound technique, we were able to make measurements, but there was an insufficient number of high resonances to uniquely determine the elastic constants. However, a larger sample yielded excellent results for all of the elastic constants.

Nonlinear pulse propagation in disordered media

Significant advances have been made in understanding the wave mechanics of disordered systems and effects such as Anderson localization, etc. Similarly, there has been considerable advance in the understanding of nonlinear systems including the behavior of solitons, etc. The study of systems which are both disordered and nonlinear is a relatively new frontier. A fundamental question is whether or not Anderson localization is weakened by the effects of nonlinearity. For continuous wave excitation, theory predicts that eigenstates remain localized; our experiments confirming this prediction have been published, as reported previously. The behavior of a pulse has been predicted to be quite different from that of continuous excitation, as follows: For a linear 1-D disordered system, the behavior of a pulse is rigorously found by making a product of matrices from one end of the system to the other, and as indicated by Furstenberg's theorem, the eigenstates would be localized and transmitted pulse energy would decrease exponentially with distance. However, a nonlinear pulse has an extra degree of freedom and can satisfy conditions locally, over some characteristic length, the "width" of the pulse. If the width of the pulse is much less than the Anderson localization length, then the disorder has no effect and the pulse is transmitted without the exponential decrease. If the pulse width is sufficiently greater than the localization length, then transmission is exponentially decreased. When the width of the pulse is on the order of

the localization length, then the pulse travels some distance with a slight decrease before an exponential decrease begins. In order to study nonlinear pulse propagation experimentally, we use surface waves on a fluid because they are intrinsically nonlinear (the speed of the surface wave depends on depth, which is modified by the presence of a finite amplitude wave). We use surface waves (third sound) in superfluid helium films to reduce viscous damping which would weaken long range phase coherence in the linear regime. The results of our experiment are now being analysed; preliminary results seem to indicate we have the first experimental confirmation of the theoretically predicted behavior.

Measurement of an extremely low (possibly the lowest) bulk infrared optical absorption

In the resonant photoacoustic project, the non-contact interdigital capacitor transducers, which were difficult to use with non-piezoelectric samples, were replaced with 9 μm piezoelectric film (PVDF) transducers. After finally taking data, the graduate student obtained results which were as good as those obtained previously with the argon laser. The student subsequently spent considerable time trying to maximize the Q of the PVDF system and in trying to increase the modulated amplitude of the infrared laser. The system has steadily improved, and the latest achievement has been the measurement of an optical absorption coefficient of $7\text{x}10^{-7}$ cm^{-1}, with a precision of $5\text{x}10^{-8}\text{cm}^{-1}$. This is an order of magnitude better than the best measurement which we have been able to find in the literature. Further improvement of our method is anticipated, perhaps using a marginal oscillator technique.

Developments in the study of fracture

In the fracture experiment we have been studying a certain type of styrofoam as a large scale model of a fracturing material. A fracture test system was developed and initial measurements were made with a bandwidth up to 100 KHz, using conventional accelerometers. However, it was realized that with a measured sound

speed of ~700 m/s and an average styrofoam cell size of 1 mm, the identification of individual cells breaking would require a time resolution of ~1 μs. We are now using a 2.25 MHz piezoelectric transducer and are observing events, in particular precursors, occurring in a few microseconds. After taking measurements for a sufficiently large number of fractures (each being a one-shot process), the data will be analysed for critical features. In order to obtain a higher frequency, broadband measurement, we are developing piezoelectric film transducers, including stack configurations.

Current and Other Funding

It is anticipated that there will be no remaining funds at the end of the contract period.

Other research grants include NSF Division of Materials Research, Low Temperature Physics Program, DMR 9306791, which includes 1 man-month of the principal investigators time.

APPENDIX: PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS SUBMITTED TO REFEREED JOURNALS
(Not yet published)

1. M. J. McKenna, P. S. Shaw, and J. D. Maynard, "A possible explanation of the normal electron persistent current discrepancy", submitted to Phys. Rev. Lett.

2. J. D. Maynard, "Classical analogs of mesoscopic quantum phenomena", to be published in Physics B.

3. M. J. McKenna, Justin Keat, Jun Wang, and J. D. Maynard, "Experiments on nonlinear wave propagation in disordered media", to be published in Physica B.

4. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "Anderson localization of 3He with variable disorder provided by a 4He solid/liquid interface", to be published in Physica B.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. J. D. Maynard, "A possible explanation of the discrepancy in electron persistent current amplitudes: A superfluid persistent current analog", J. Low Temp. Phys. **89**, 155-159 (1992)

2. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Using acoustic resonators to study superfluid-filled silica aerogel, high Tc superconductors, and quasicrystals", J. Low Temp. Phys. **89**, 689-693 (1992)

3. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "Observation of two-stage layering transitions for solid 4He on graphite", Phys. Rev. Lett. **69**, 3346-3349 (1992)

BOOKS (AND SECTIONS THEREOF) PUBLISHED

1. J. D. Maynard, M. J. McKenna, A. Migliori, and W. M. Visscher, "Ultrasonic Measurements of Elastic Constants in Single Crystals of La_2CuO_4", in *Ultrasonics of High-Tc and Other Unconventional Superconductors* , ed. M. Levy, (Academic Press, Boston, 1992) p. 381-408

2. J. D. Maynard, "Tuning up a quasicrystal", in *Perspectives in Physical Acoustics* , ed Y. Fu, R. K. Sundfors, and P. Suntharothok (World Scientific, Singapore, 1992) p. 201-236

3. J. D. Maynard, "Learning about phonons with frequencies below one KHz", in *Phonon Scattering in Condensed Matter VII* , ed M. Meissner and R. O. Pohl, (Springer-Verlag, Berlin, 1993) pp. 239-243

TECHNICAL REPORTS AND THESES PUBLISHED

None

BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATIONS

1. J. D. Maynard, "Acoustical Holography", to be published as a chapter in *Handbook of Acoustics* , ed. M. J. Crocker (John Wiley and Sons, New York)

2. J. D. Maynard, "Phonons in Crystals, Quasicrystals, and Anderson Localization" to be published as a chapter in *Handbook of Acoustics* , ed. M. J. Crocker (John Wiley and Sons, New York)

INVITED PRESENTATION AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Colloquium, Department of Physics, West Virginia University, December 3, 1992, "Tuning-up a Quasicrystal", Thomas Myers, host

2. Colloquium, Department of Physics, Washington University, St. Louis, MO January 13, 1993, "Tuning-up a Quasicrystal", J. E. Shrauner, host

3. Invited Symposium Lecture, 124th Meeting of the Acoustical Society of America, New Orleans, October 1992, "Using piezoelectric film and resonant ultrasound to determine the elastic tensor of small, fragile samples"

4. Invited Symposium Lecture, 125th Meeting of the Acoustical Society of America, Ottawa, Ontario, May, 1993, "Pulses, nonlinearity, and Anderson localization"

5. Invited Lecture, 20th International Meeting of Low Temperature Physics, Eugene, Oregon, August 1993, "Classical analogs of mesoscopic quantum phenomena"

6. Colloquium, Department of Physics, University of Oregon, Eugene, OR, October 7, 1993, Martin Weybourne, host

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Application of resonant ultrasound spectroscopy to the study of small single crystal wafers", J. Acoust. Soc. Am. **92**, 2313 (1992).

2. J. D. Maynard, J. Keat, and M. J. McKenna, "Experiments on nonlinear pulse propagation in disordered media", Bull. Am. Phys. Soc. **38**, 384 (1993)

3. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Elastic constants of TiB2 and SiC using resonant ultrasound spectroscopy", Bull. Am. Phys. Soc. **38**, 677 (1993)

4. M. J. McKenna, P. S. Spoor, and J. D. Maynard, "Elastic constants of quasicrystalline and R-phase cubic AlCuLi using resonant ultrasound spectroscopy", Bull. Am. Phys. Soc. **38**, 681 (1993)

5. V. Hopkins, M. J. McKenna, and J. D. Maynard, "The use of 3He NMR as a probe of the nature of the 4He solid/superfluid interface", Bull. Am. Phys. Soc. **38**, 1042 (1993)

6. M. J. McKenna, M. J. Baloh, and J. D. Maynard, "An annular first, second, and fourth sound resonator for studying the superfluid transition dimensional crossover and finite amplitude effects", Bull. Am. Phys. Soc. **38**, 1042 (1993)

7. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "A comparison of elastic constants of the quasicrystalline and cubic approximant phases of AlCuLi, using resonant ultrasound spectroscopy", J. Acoust. Soc. Am. **93**, 2276 (1993).

8. M. J. McKenna, Wei-li Lin, and J. D. Maynard, "Using piezoelectric film and resonant ultrasound for photoacoustic measurements of very low optical absorption in piezoelectric and dielectric crystals", J. Acoust. Soc. Am. **93**, 2276 (1993).

HONORS/AWARDS/PRIZES AND PATENTS/APPLICATIONS

None

GRADUATE STUDENTS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1993

1. Philip Spoor (Ph.D. candidate, acoustics) Elastic Constants for Aluminum Alloy Quasicrystals and High Tc Superconductors

2. Vern Hopkins (Ph.D. candidate, physics) NMR measurements for 3He at the 4He quantum solid/liquid interface
Began Fall 1990

3. Wei-Li Lin (Ph.D. candidate, physics) Infrared resonant photoacoustics
Began Summer 1991

4. John McGillivray (MS candidate, acoustics) Fracture
Summer 1993

5. David Vituccio (Ph.D. candidate, physics) Thermoacoustic heat engines
Summer 1993

POSTDOCTORALS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1993

Mark McKenna, Research Associate, July 1, 1989 to July 31, 1993

MISCELLANEOUS

Undergraduates Involved in Research:

1. Michael Baloh, Senior 1993
2. Steve Savitsky, Senior 1993
3. Jason White (Research Experience for Undergraduates student, summer 1993)